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Acoustic Converting Efficiency and Anisotropic Nature of Wood

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It is accepted that both the acoustic converting efficiency and the degree of anisotropy of wood are important factors for the sound board of musical instruments[1,2]. In this paper, the relationship between these factors were clarified experimentally and theoretically. The specific dynamic Young's modulus (E'/ρ) and the loss tangent ($\tan\delta_L$) in the longitudinal (L) direction, and the dynamic shear modulus (G') and the loss tangent ($\tan\delta_S$) in the LT plane (T : tangential direction) for 101 kinds of woods were measured by using flexural and torsional vibration methods.

There was a negative correlation between E'/ρ and $\tan\delta_L$ as shown in Fig. 1. This fact indicates that smaller mean microfibril angles give larger E'/ρ and lower $\tan\delta_L$ values[3]. Fig. 2 shows the relationships between the ratio of loss tangents ($\tan\delta_S/\tan\delta_L$) and that of elastic moduli (E'/G'). Relatively large E'/G' and $\tan\delta_S/\tan\delta_L$ values of wood reflect its anisotropic nature. Fig. 3 shows the relationship between (E'/G') ($\tan\delta_S/\tan\delta_L$) and $\sqrt{E'/\rho}/\tan\delta_L$. The former reflects the degree of anisotropy and the latter relates to the acoustic converting efficiency ($\sqrt{E'/\rho^3}/\tan\delta_L$). There was a positive correlation between them. These acoustic properties can be calculated by using a uniaxiall cell wall model in which amorphous isotropic matrix is disposed in parallel along the axis of cellulosic fibrils inclining at θ to the L direction of wood[4]. The E'/ρ, $\tan\delta_L$, G'/ρ and $\tan\delta_S$ can be expressed by

$$\frac{E'}{\rho}\approx\frac{\nu}{\rho_w}\left(\frac{1}{E_{w1}'}+\frac{\theta^2}{G_{w12}'}\right)^{-1},\quad \tan\delta_L\approx\left(\frac{E_{w1}''}{E_{w1}'^2}+\frac{G_{w12}''\theta^2}{G_{w12}'^2}\right)\left(\frac{1}{E_{w1}'}+\frac{\theta^2}{G_{w12}'}\right)^{-1},$$

$$\frac{G'}{\rho}\approx\frac{\nu}{\rho_w}\left(\frac{\sin^2 2\theta}{E_{w1}'}+\frac{\cos^2 2\theta}{G_{w12}'}\right)^{-1}$$

and

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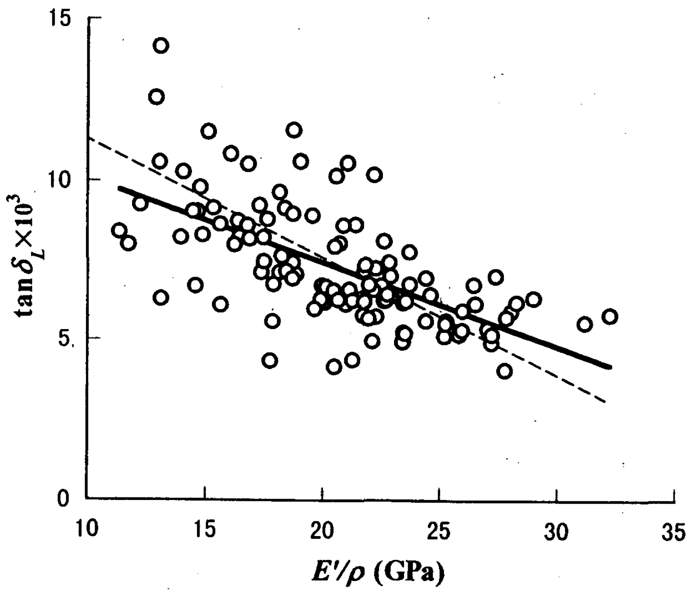

Fig. 1. The relationship between the loss tangent ($\tan \delta_L$) and the specific dynamic Young's modulus (E'/ρ) in the longitudinal direction of wood. Note: O, Experimental values; solid line, the reglession line of experimental values ($r=-0.632$); dotted line, calculated values.

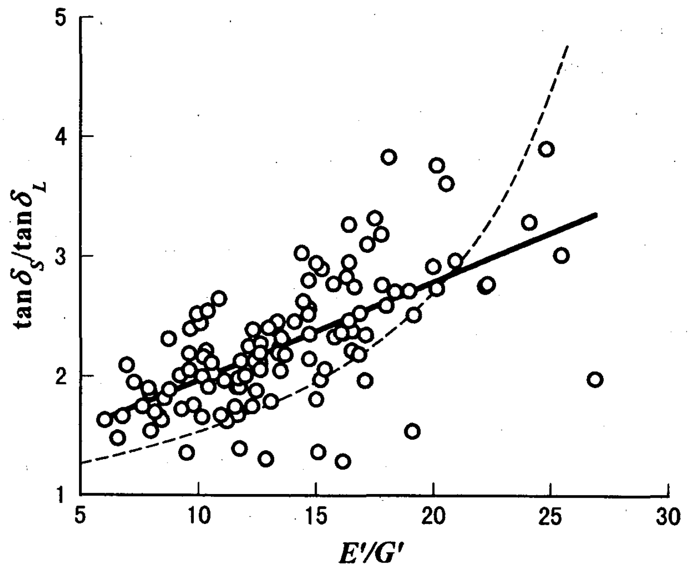

Fig. 2. The relationship between the ratio of loss tangent ($\tan \delta_S/\tan \delta_L$) and that of elastic moduli (E'/G') of wood. Note: O, Experimental values; solid line, the reglession line of experimental values ($r=0.648$); broken line, calculated values.

$$\tan \delta_S \approx \left(\frac{E_{w2}'' \sin^2 2\theta}{E_{w2}'^2} + \frac{G_{w12}'' \cos^2 2\theta}{G_{w12}'^2}\right)\left(\frac{\sin^2 2\theta}{E_{w2}'} + \frac{\cos^2 2\theta}{G_{w12}'}\right)^{-1},$$

where ν is the volume fraction of S_2 layer, E_{w1} and E_{w2} are the Young's moduli of the cell wall in the parallel (1) and perpendicular (2) to the axis of fibrils, G_{w12} is the shear modulus of the

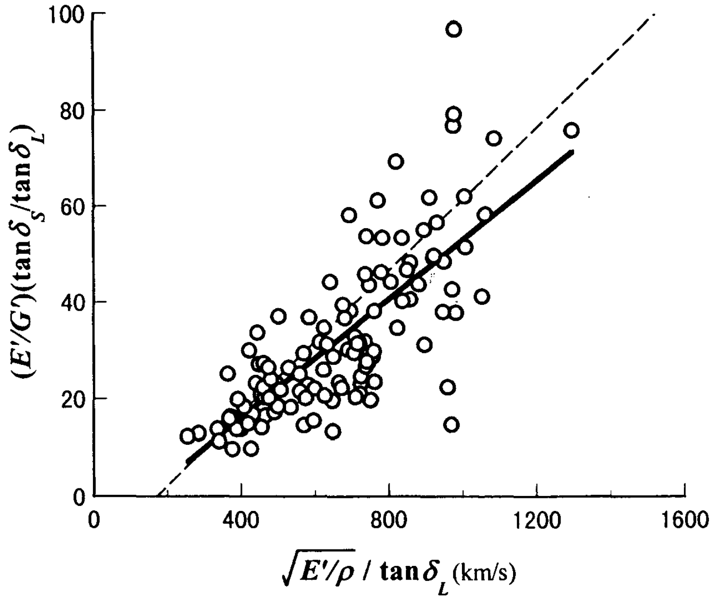

Fig. 3. The relationship between the (E'/G') $(\tan \delta_S/\tan \delta_L)$ and the sound velocity divided by the loss tangent $(\sqrt{E'/\rho}/\tan \delta_L)$ of wood. Note: O, Experimental values; line, the reglession line of experimental values ($r=0.752$) broken line, calculated values.

cell wall in the 1–2 plane, ρ_w is the density of the cell wall, respectively. Single and double primes indicate the dynamic modulus and loss modulus, respectively. According to the law of mixtures, E_{w1}', E_{w1}'', E_{w2}', E_{w2}'', Gw_{12}' and G_{w12}'' can be expressed by

$$E_{w1}'=\varphi E_{f1}+(1-\varphi)E_m,\ E_{w1}''=(1-\varphi)E_m''=(1-\varphi)E_m' \tan\delta_m,$$

$$E_{w2}'\approx E_m'\left(1+\frac{\varphi}{1-\sqrt{\varphi}}\right),\ E_{w2}''\approx E_m'\left(1+\frac{\varphi}{1-\sqrt{\varphi}}\right)\tan\delta_m,$$

$$G_{w12}'\approx G_m'\left(1+\frac{\varphi}{1-\sqrt{\varphi}}\right) \text{ and } G_{w12}''\approx G_m'\left(1+\frac{\varphi}{1-\sqrt{\varphi}}\right)\tan\delta_m,$$

where E_{f1} is the Young's modulus of fibrils along the axis, φ is the volume fraction of fibrils, E_m', G_m' and $\tan\delta_m$ are the Young's modulus, shear modulus and loss tangent of the matrix, respectively. Values of $\nu=0.84$, $E_{f1}=134$ GPa, $\varphi=0.5$, $E_m=2$ GPa, $G_m=0.77$ GPa, and $\tan\delta_m=0.015$ were adopted. Dotted lines in Figs. 1–3 show the calculated values. The calculated values in Fig. 3 predicted that smaller microfibril angles give higher values of acoustic converting efficiency as well as higher degrees of anisotropy.

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